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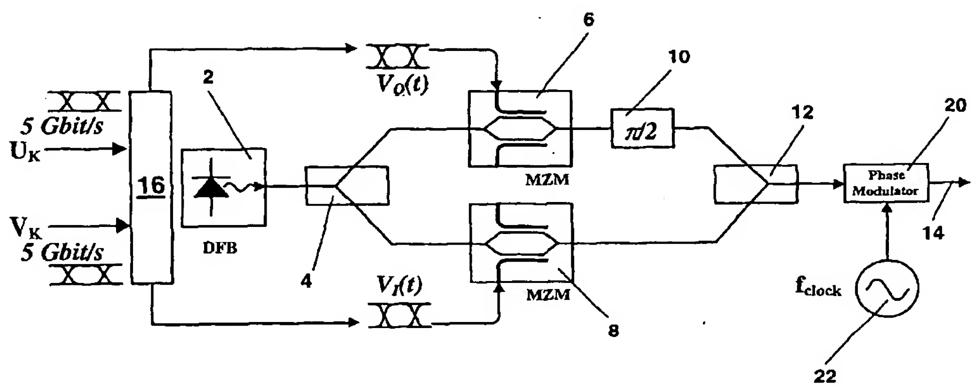
(54) Title: OPTICAL EXTERNAL DPQSK MODULATOR WITH SUBSEQUENT PRECHIRPING



(57) Abstract: A modulator arrangement for modulating an optical signal using a differential quadrature phase shift key for use in an optical wavelength division multiplex (WDM) optical communications system comprising a laser for producing an optical signal of a selected wavelength, which signal is split by a splitter (4), each part of said split signal being applied to a respective phase modulator (6, 8). The phase modulators (6, 8) are adapted to modulate the phase of the signal in dependence on a respective drive voltage and the phase of the output of at least one modulator is shiftable. The split signals are recombined by an optical recombiner (12) to form an optical phase shift key output. The arrangement further comprises a phase modulator (20) adapted to chirp the optical phase shift key output.

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Photonic Encoder

The invention relates to a method and apparatus for encoding an optical signal having improved dispersion tolerance in a wavelength division multiplex (WDM) optical communications system.

In this specification the term "light" will be used in the sense that it is used generically in optical systems to mean not just visible light but also electromagnetic radiation having a wavelength between 800 nanometres (nm) and 3000nm. Currently the principal optical communication wavelength bands are centred on 1300nm, 1550nm (C-Band) and 1590nm (L-Band), with the latter bands receiving the majority of attention for commercial exploitation.

Exemplary WDM systems operating in the 1550nm C-Band optical fibre communication band are located in the infrared spectrum with International Telecommunication Union (ITU) 200, 100 or 50 GHz channel spacing (the so called ITU Grid) spread between 191 THz and 197THz.

With ongoing developments in optically amplified dense wavelength division multiplex (DWDM) optical links as the backbone of point-to-point information transmission and the simultaneous increase in bit rate applied to each wavelength and the simultaneous increase in the number of channels, the finite width of the erbium gain window of conventional erbium-doped optical amplifiers (EDFAs) could become a significant obstacle to further increases in capacity. Conventional EDFAs have a 35nm gain bandwidth which corresponds to a spectral width of 4.4 THz. System demonstrations of several Tbit/s data rate are already a reality and the spectral efficiency, characterised by the value of bit/s/Hz transmitted, is becoming an important consideration. Currently, high-speed optical transmission mainly employs binary amplitude keying, using either non-return-to-zero (NRZ) or return-to-zero (RZ) signalling formats, in which data is transmitted in the form of binary optical pulses, i.e. on or off.

In WDM several factors limit the minimum channel spacing for binary amplitude signalling, and in practice spectral efficiency is limited to ~0.3 bit/s/Hz. Although

increasing the per-channel bit rate tends to reduce system equipment, there are several problems that need to be overcome for transmission at bit rates above 10 Gbit/s; these being:

- dispersion management of the optical fibre links, this becomes increasingly difficult with increased bit rate;
- Polarisation mode dispersion (PMD) in the optical fibre causes increased signal degradation;
- Realisation of electronic components for multiplexing, de-multiplexing and modulator driving becomes increasingly difficult.

One technique which has been proposed which allows an improvement of spectral efficiency is the use of quadrature phase shift keying (QPSK) [S. Yamazaki and K. Emura, (1990) "Feasibility study on QPSK optical heterodyne detection system", J. Lightwave Technol., vol. 8, pp. 1646-1653]. In optical QPSK the phase of light generated by a transmitter laser is modulated either using a single phase modulator (PM) driven by a four-level electrical signal to generate phase shifts of 0, $\pi/2$, π or $3\pi/2$ representative of the four data states, or using two concatenated phase modulators which generate phase shifts of 0 or $\pi/2$ and π or $3\pi/2$ respectively. A particular disadvantage of QPSK is that demodulation requires, at the demodulator, a local laser which is optically phase-locked to the transmitter laser. Typically this requires a carrier phase recovery system. For a WDM system a phase-locked laser will be required for each wavelength channel. It further requires adaptive polarisation control which, in conjunction with a phase recovery system, represents a very high degree of complexity. Furthermore, systems that require a coherent local laser are sensitive to cross-phase modulation (XPM) in the optical fibre induced by the optical Kerr non-linearity, which severely restricts the application to high capacity DWDM transmission.

It has also been proposed to use differential binary phase shift keying (DBPSK) [M. Rohde et al (2000) "Robustness of DPSK direct detection transmission format in standard fibre WDM systems", Electron. Lett., vol. 36]. In DBPSK data is encoded in the form of phase transitions of 0 or π in which the phase value depends upon the phase of the carrier during the preceding symbol interval. A Mach-Zehnder

interferometer with a delay in one arm equal to the symbol interval is used to demodulate the optical signal. Although DBPSK does not require a phase-locked laser at the receiver it does not provide any significant advantages compared to conventional amplitude NRZ signalling.

US 6271950 discloses a differential phase shift keying optical transmission system, comprising a laser to generate an optical signal, a delay encoder to provide a different delay for each of M input channels and an M channel phase modulator which phase modulates the optical carrier signal with each of the differently delayed M input signal channels to form a time division multiplex (TDM) phase modulated optical signal.

However, in modern communication systems, the rate of development dictates that typically data streams multiply up by a factor of 4 every few years. At the time of application the proposed standard installation will use data streams of 10 Gbit/s and systems of 40 Gbit/s have been demonstrated. In addition to the matters discussed above, the practical problem then arises that new systems operating at high speeds have to co-operate with older systems.

The present invention seeks to provide an encoder for an optical signal having improved dispersion tolerance.

According to the invention, there is provided a modulator arrangement for modulating an optical signal using a differential quadrature phase shift key for use in an optical wavelength division multiplex (WDM) optical communications system comprising a laser for producing an optical signal of a selected wavelength, which signal is split by a splitter, each part of said split signal being applied to a respective phase modulator, each of which phase modulators is adapted to modulate the phase of the signal in dependence on a respective drive voltage, the phase of the output of at least one modulator being shiftable, the split signals being recombined by an optical recombiner to form an optical phase shift key output, wherein the arrangement further comprises means adapted to chirp the optical phase shift key output.

In this context, chirping relates to the variation of an optical signal's phase modulation: amplitude modulation ratio. Chirping the optical PSK output modifies

the evolution of the optical signal along a length of dispersive fibre. Surprisingly, applying chirp to the phase modulated signal external to the phase modulators does not result in any significant corruption of the data signal and reduces the need for chromatic dispersion compensation that would otherwise be required. For short haul systems operating at 10Gbit/s, a chirped optical PSK signal can be transmitted up to around 300km before any chromatic dispersion compensation is required in contrast to the known prior art systems where compensation is usually required after about 80km.

Preferably, the arrangement comprises a phase modulator adapted to chirp the optical PSK output. Preferably, the phase modulator applies a $\pi/4$ phase modulation to the output signal. Preferably, the phase modulator is driven by a oscillator which is phase locked with the data streams. Preferably, the phase modulator comprises an electrode over a waveguide through which the optical output propagates. Preferably, the system is used with 10 Gbit/s data streams.

An exemplary embodiment of the invention will now be described in greater detail with reference to the drawing in which:

Fig. 1 shows a modulator arrangement;
Fig. 2 shows comparative graphs of eye opening against fibre length

Referring to Figure 1 there is shown an optical phase shift key modulator arrangement in accordance with the invention for encoding two 5 Gbit/s NRZ data streams U_k,V_k onto a single optical carrier. Typically the modulator arrangement would be used as part of a transmitter in a WDM optical communications system with a respective modulator arrangement for each WDM wavelength channel.

The modulator arrangement comprises a single frequency laser 2, for example a distributed feedback (DFB) semiconductor laser due to its stable optical output for a given wavelength, which is operated to produce an unmodulated optical output of a selected wavelength, typically a WDM wavelength channel. Light from the laser is divided by an optical splitter 4 into two parts and each part is applied to a respective

phase modulator 6, 8. Each phase modulator 6, 8 is configured such that it selectively modulates the phase by 0 or π radians in dependence upon a respective binary (bipolar) NRZ drive voltage $V_I(t)$, $V_Q(t)$. In the preferred arrangement illustrated in Figure 1 the phase modulators 6, 8 each comprise a Mach-Zehnder electro-optic modulator (MZM) which is fabricated for example in gallium arsenide or lithium niobate. As is known MZMs are widely used as optical intensity modulators and have an optical transmission versus drive voltage characteristic which is cyclic and is generally raised cosine in nature. The half period of the MZM's characteristic, which is measured in terms of a drive voltage, is defined as V_π. Within the modulator arrangement of the present invention each MZM 6, 8 is required to operate as a phase modulator without substantially affecting the amplitude (intensity) of the optical signal. To achieve this each MZM 6, 8 is biased for minimum optical transmission in the absence of a drive voltage and is driven with a respective drive voltage $V_I(t)$, $V_Q(t) = \pm V_\pi$ to give abrupt phase shifting with a minimum of amplitude modulation. The two phase modulators 6, 8 have matched delays (phase characteristics).

The optical output from the phase modulator 6 is passed through a phase shifter 10 which effectively applies a phase shift of $\pi/2$ such that the relative phase difference between the optical signals passing along the path containing the modulator 6 and that passing along the path containing the modulator 8 is $\pm\pi/2$. The optical signals from the phase shifter 10 and phase modulator 8 are recombined by an optical recombiner 12, to form an optical phase shift key (PSK) output 14. The splitter 4 comprises a 1x2 MMI (multimode interference coupler) and recombiner 12 comprises a 2x2 MMI. The two MMIs co-operate to provide a phase shift to the signal of about $\pi/2$. A control electrode is then used to provide the fine control. There are of course alternative methods of obtaining a $\pi/2$ shift in one of the arms, such as using a control electrode to provide the entire shift. When using GaAs technology, MMIs are etched into the epitaxial layer, which etch is deeper than the cut for the main waveguide.

A further phase modulator 20 is provided after the recombiner 12 to chirp the optical PSK output 14, which phase modulator 20 is driven at a clock rate corresponding to the data line rate. For example in a 10Gbit/s QPSK system, the clock rate is 5GHz. The oscillator 22 which provides the 5GHz clock rate must be synchronous with the

data clock rate, i.e. it should be phase locked with the data stream. At these clock speeds, there is a delay of several symbol periods between the precoder and the output, so the phase of the clock signal applied to the phase modulator 20 should be adjusted to match.

The phase modulator 20 comprises a single electrode over the waveguide, which arrangement will minimise insertion losses. The modulator 20 needs to be external to the MZIs 6, 8 to avoid corruption of the phase modulated data signal.

The phase modulator drive voltages $V_I(t)$, $V_Q(t)$ are generated by pre-coding circuitry 16 in dependence upon the two binary data streams U_k, V_k. According to the modulator arrangement of the present invention the two data streams U_k, V_k are differentially encoded such that these data are encoded onto the optical signal 14 in the phase transitions (changes) rather than in the absolute phase value. The optical signal 14 is differential quadrature phase shift key (DQPSK) encoded.

The DQPSK optical signal 14 is ideally given by $E_0 \exp(i\omega t + \theta + \theta_i)$, where ω is the mean optical angular frequency, t is time, θ the carrier phase and θ_i a data dependent phase modulation for the i-th data symbol d_i. In the general case $d_i \in \{0,1,\ldots M-1\}$ and for quarternary phase shift keying M=4, that is the data symbol has four values. The phase modulation term is given by $\theta_i = \theta_{i-1} + \Delta\theta_i(d_i)$ in which θ_{i-1} is the phase term for the previous data symbol d_{i-1} and $\Delta\theta_i$ the change in phase between the i_{-1} and i-th data symbols. The relationship between data symbol d_i and phase shift $\Delta\theta_i$ for QPSK is tabulated below.

U_k	V_k	d_i	$\Delta\theta_i\,(d_i)$
0	0	0	0
0	1	1	$\pi/2$
1	0	2	π
1	1	3	$3\pi/2$

Table 1 Values of data U_k, V_k, data symbol d_i and phase change $\Delta\theta_i(d_i)$ for DQPSK.

Figure 2 shows a comparative graph of the relative eye opening against fibre length for a conventional NRZ amplitude signal, a phase modulated differential binary PSK signal and a differential quadrature PSK signal for a 10 Gbit/s data rate.

As the graph shows a conventional NRZ amplitude signal degrades steadily with fibre length and has an effective useful length of between 75 and 100km. The duobinary signal is better having a useful length of around 250km. In contrast the phase modulated differential quadrature signal according to the invention has an effective length of in excess of 300 km.

Claims

1. A modulator arrangement for modulating an optical signal using a differential quadrature phase shift key for use in an optical wavelength division multiplex (WDM) optical communications system comprising a laser for producing an optical signal of a selected wavelength, which signal is split by a splitter, each part of said split signal being applied to a respective phase modulator, each of which phase modulators is adapted to modulate the phase of the signal in dependence on a respective drive voltage, the phase of the output of at least one modulator being shiftable, the split signals being recombined by an optical recombiner to form an optical phase shift key output, wherein the arrangement further comprises means adapted to chirp the optical phase shift key output.

2. A modulator arrangement according to Claim 1, wherein the arrangement comprises a phase modulator adapted to chirp the optical PSK output.

3. A modulator arrangement according to Claim 2, wherein the phase modulator applies a $\pi/4$ phase modulation to the output signal.

4. A modulator arrangement according to Claim 2 or Claim 3, wherein the phase modulator is driven by a oscillator which is phase locked with the data streams.

5. A modulator arrangement according to any one of Claims 2 to 4, wherein the phase modulator comprises an electrode over a waveguide through which the optical output propagates.

6. A modulator arrangement according to any one of Claims 1 to 5, wherein the system is used with 10 Gbit/s data streams.

7. A modulator arrangement substantially as described herein, with reference to and as illustrated in the accompanying drawings.

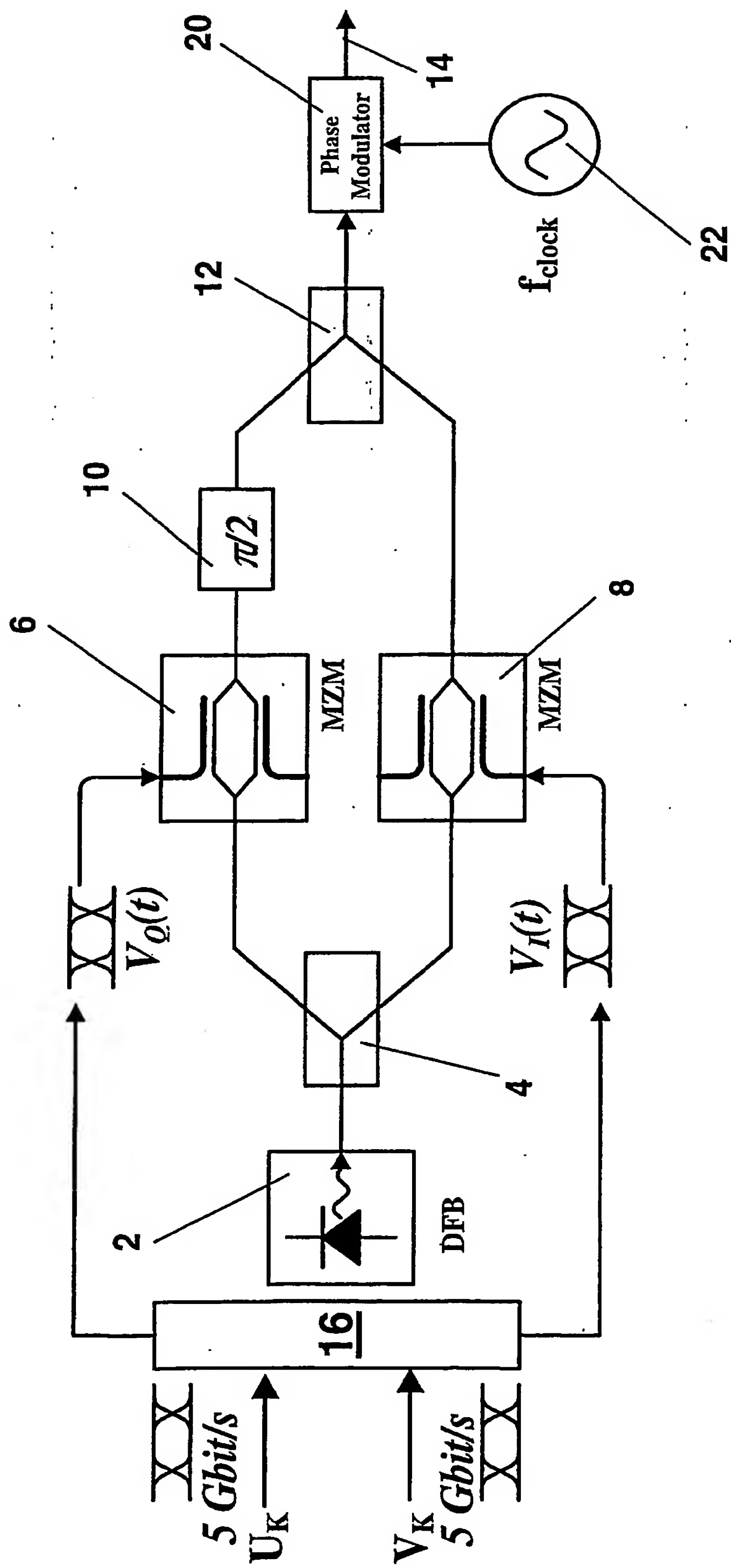
20
14
Phase Modulator
f_{clock}
22
12
10
π/2
6
8
MZM
MZM
$V_Q(t)$
$V_I(t)$
4
2
DFB
16
5 Gbit/s
U_K
V_K
5 Gbit/s

Figure 1.

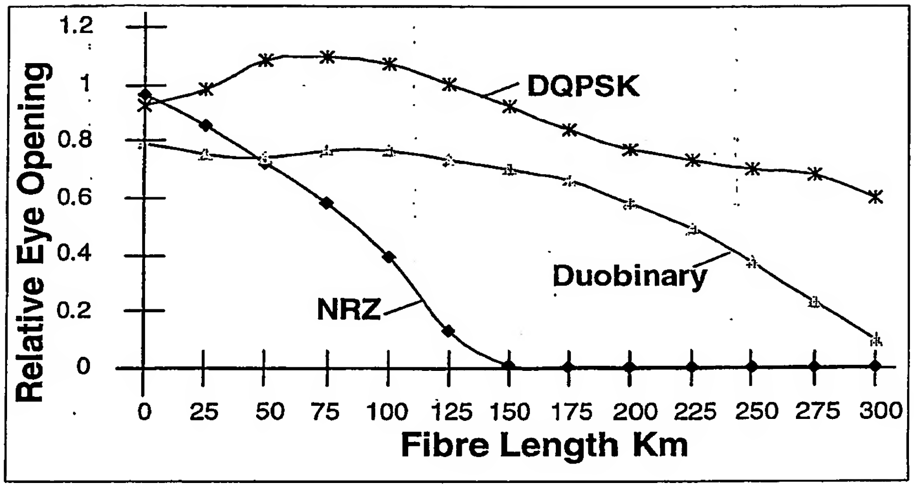
Relative Eye Opening
1.2
1
0.8
0.6
0.4
0.2
0
0 25 50 75 100 125 150 175 200 225 250 275 300
Fibre Length Km
DQPSK
Duobinary
NRZ

Figure 2.

INTERNATIONAL SEARCH REPORT

In ›nal Application No
PC1/GB 02/05386

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B10/155 H04B10/18 H04L27/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B H04L H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, PAJ, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4 893 352 A (WELFORD DAVID) 9 January 1990 (1990-01-09) abstract column 1, line 58 -column 2, line 34 column 3, line 19 -column 3, line 35 column 5, line 4 - line 20 figure 7 ---	1-7
Y	US 5 222 103 A (GROSS RICHARD W) 22 June 1993 (1993-06-22) abstract column 1, line 60 - line 64 figures 1,3 --- -/--	1-7

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 01 08336 A (TYCO SUBMARINE SYSTEMS LTD) 1 February 2001 (2001-02-01) abstract page 7, paragraph 2 page 8, paragraph 5 page 9, paragraph 5 page 19, paragraph 3 figure 2	1-7
A	MURAKAMI M ET AL: "Transoceanic twelve 10 Gbit/s WDM signal transmission experiment with individual channel dispersion-and-gain compensation and prechirped RZ pulse format" ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 33, no. 25, 4 December 1997 (1997-12-04), pages 2145-2146, XP006008255 ISSN: 0013-5194 abstract page 2145, paragraph 3 figure 1	1-7
A	KODAMA Y ET AL: "Analytical theory of guiding-center nonreturn-to-zero and return-to-zero signal transmission in normally dispersive nonlinear optical fibers" OPTICS LETTERS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, US, vol. 20, no. 22, 15 November 1995 (1995-11-15), pages 2291-2293, XP002230089 abstract page 2292, paragraph 2 -page 2293, paragraph 1	1-7

INTERNATIONAL SEARCH REPORT

Ir onal Application No
PCT/GB 02/05386

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 4893352	A	09-01-1990	NONE		
US 5222103	A	22-06-1993	NONE		
WO 0108336	A	01-02-2001	US	6341023 B1	22-01-2002
			WO	0108336 A1	01-02-2001